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Getting students hooked on systems engineering!

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Abstract

The author has reported most recently at IS2012 about initiatives in the Norwegian University of Science and Technology to help students learn about SE by doing SE. She address the question, "lacking a degree program in the university dedicated to SE, what is the best way to give students a taste of SE that makes them want more?" Success of the efforts to date has been indicated by a 100% employment in Norway of all students who demonstrate an awareness of and willingness to learn more about SE.

The paper describes three initiatives: results from a PhD level course that has run for 12 years, including publications; lab exercises for a master level course on Industrial Design-SE that has run for 3 years; and a master thesis project that has experienced recent success attributed to the introduction of a systems engineer role on the project team since 2011.

The conclusion is that letting students 'try out' systems engineering practices in a laboratory/project environment offers them learning experiences that clearly demonstrate the value of systems engineering practices and theory.

Keywords: systems engineering; systems engineering education; learning by doing

1. Introduction

1.1. The history of systems engineering at NTNU

Professor Odd Andreas Asbjørnsen of the faculty of Natural Science and Engineering, department of Energy and Process Engineering was the first to introduce systems engineering to the university. In 1994 he returned from sabbatical at the University of Maryland, a member of INCOSE (#49), with a primer that he had written for Norwegian students [1]. Two PhD's in systems engineering graduated before he retired in 1999. Professor Annik Magerholm Fet and Associate Professor Hans Jørgen Dahl have each promoted systems thinking and systems engineering in their respective courses. A course introduced by professor Asbjørnsen for masters' capstone projects was taken up by Professor Dahl and developed into a PhD course in 2001.

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Shortly after the author completed her PhD in 2005, she was approached by the department of Production and Quality Engineering to develop a masters-level course in Industrial Design – Systems Engineering that would be open to students from all study programs. This course has been offered since spring 2010, and attracted engineering and non-engineering majors alike. The same year, a student from that debut course joined a project team sponsored by the department of Product Development and Materials for his masters' thesis. The project team was having difficulties and he suggested that they consider using a systems engineering approach to help systematize and execute their project. The results of this decision, to use systems engineering, was presented by Haskins and Welland [2] at IS2012. The project continues to include at least one student in the role of systems engineer each year.

1.2. The new generation of engineering education

In 1993 Professor Asbjørnsen formulated the following needs statement for the 'customers' of education, namely the students: "… to prepare for the tasks and challenges posed by commercial and public activities in pursuing a career in the profession of choice and to further grow in their intellectual abilities and knowledge." [3: 339]

He is joined by a chorus of educators who have recognized the need for practice-based curriculum and physical facilities (workshops and laboratories) that take the student out of the lecture hall, and into an arena where they can exercise their theory, make mistakes and apply some creativity. In describing their Learning Factory, Lamancusa et. al. write of the "… need for both intellectual and physical activities in order to anchor the knowledge and practice of engineering in the minds of the students." [4: 103] Without these tangible opportunities, engineering students may fail to see the relevance of the required courses [9].

1.3. The importance of industrial partners

NTNU prides itself on its close ties with local and national industry partners. Subject matter experts are invited regularly to present themselves, their company, and their area of expertise as part of the in-class and extra-curricular lectures. Students gain an early appreciation that the theories they are learning have practical application, at the same time making early determinations about the kind of work they want to do after graduation. Industrial partners open their doors for PhD and master's level research, and their wallets to sponsor special high-visibility projects.

2. Results from systems engineering curricular activities at NTNU

2.1. PhD courses at NTNU

Since 1997 NTNU has granted PhD diplomas to three candidates for research in systems engineering. They are Professor Annik Magerholm Fet, in 1997 for applications of systems engineering to the lifecycle analysis of ships; Dr. Hans Jørgen Dahl, in 1999, for the application of systems engineering to the analysis of market opportunities for Norwegian natural gas; and, the author, in 2005, for the application of systems engineering to issues in sustainable development. All three have remained active proponents of systems engineering in their course work, and their support of the Norwegian chapter of INCOSE.

Professor Fet teaches a PhD methods course that introduces systems engineering as a method. Four papers have been published in Systems Engineering from the essay written for this course by candidates Haskins [10, 11], Sopha [12], and Schau [13]. For 12 years, Associate Professor Dahl taught a PhD level course, Systems Engineering Principles and Practice, which focused on understanding the research problem domain using information modeling as described in "Engineering Complex Systems" by Oliver, Kelliher, and Keegan [5]. Forty students have written their essay on the application of these techniques to their own PhD research domain. The research domains include: building, IT, production and design, energy systems, maritime and aquaculture, offshore platforms, and project management. Three articles have been published in Systems Engineering from this course from candidates Nøsterbø [14], Shainee [15], and Ramirez [16]. Professor Dahl established his own measure of effectiveness for this course –

that over 90% of the students would evaluate the course as valuable to the PhD research. He achieved this goal every year. The author will continue this course again in spring 2013.

2.2. Industry partners for PhD reports

PhD work at NTNU is often financed by The Research Council of Norway, in this case 7 of 40 students. Statoil (StatoilHydro and Gassco) provided support for 9 of these 40 reports. The next level of support with 3-4 projects each was provided by SINTEF Energy Research, Statkraft, Aker Solutions, Marintek, and Det norske Veritas. Rounding out the list of industrial supporters are ABB, Brunvoll, Domstein Måløy, HÅG, Jotun, IBM, IKM Ocean Design, and Smart Motor.

3. Masters course at NTNU

Spring 2010, the department of Production and Quality Engineering started a course on Industrial Design-Systems Engineering. This is an open course that also attracts participation from across the campus. From the beginning, it was agreed that the lab and practical work would count for 40% of the course credit. In the first year, the students conducted an analysis of the feasibility of a plant expansion for a local manufacturer. The 25 students worked in teams of 5 and produced impressive results based on very minimal information and a plant visit.

Inability to create a pipeline of available projects that would enable the students to apply systems engineering approaches motivated a change to a 100% exam evaluation and a risk-free, grade-free lab that allowed the students to build a manufacturing system according to loosely defined specifications using Lego Mindstorms® parts and processors. The second cohort for this course included 27 students, of whom only 4 had a strong engineering background. The lab for year 2 was very simple, but was still both fun and challenging. In the third year, there were 27 students, most with mechanical, electrical or mechatronic background, and highly motivated. They were challenged to use concurrent engineering to design and build a car manufacturing plant using the Lego Mindstorms® parts and processors. The results from the labs were impressive given the skills of the class populations, and interested persons can watch the final demonstrations for 2011 [6] and 2012 [7] on YouTube.

As part of the NTNU commitment to continuous improvement in teaching, a reference group is formed for each course at the undergraduate and graduate levels. The feedback from the students is that use of the Lego Mindstorms® should be continued as it provides a context of 'serious play' [8]. Each year the assessment is that SE is not intuitive at first, but becomes clearer before the end of the semester. They often learn more about the value of SE if they lose some time in "trial and error" design in the lab. For the instructor, it is a fine balance for just how much struggle is useful versus frustrating. Word of mouth has ensured full class enrollment every year.

4. Shell Eco Marathon Competition

The Shell Eco-marathon (SEM) is a worldwide competition to challenge university students to design, build and run the ultimate fuel-efficient vehicle [18]. NTNU has competed in the SEM since 2008 and still holds the world record within the Urban Concept Fuel Cell class [17].

However, following their outstanding performance in 2009, the SEM2010 team experienced problems with further development of the car. They did not allocate any time for integration testing before the race. And, although every component worked well individually, as a complete system the car failed. When they arrived at the race site they were rejected due to problems with the brakes, hydrogen system and control system, which meant that there was no result in 2010 from NTNU. The goal of the SEM2011 team was to win again in the Urban Concept Fuel Cell class. The paragraphs that follow on SEM2011 are excerpted from Haskins and Welland [2].

4.1. The SEM race 2011

Understandably, the team corporate sponsor was hesitant about continuing their support, and delayed their decision until late in December 2010. Until then, the team was understaffed and morale was low. When the sponsor commitment was received, the small decided to add a systems engineer to the team to have any chance of success. Finally, in January, the team reached full strength with one project manager, one systems engineer and 5 engineers with engineering educational backgrounds in mechanical, ICT and Cybernetics. It should be noted that the SE methodology used was tailored by the student to fit the circumstances of the project; namely a challenging problem, a very tight schedule, limited resources, and a customer/sponsor who expected superior results.

Educating the Team. Before the systems engineer joined the team in January, the core team, including the project manager, received a brief training session given by the author. This convinced the team how important it was to have a systems engineer on board before further development of the car, primarily to reduce the risk of making the same mistakes as the prior year's team.

Shortly after the systems engineer, Alexander, joined the team, it was decided that there should be a whole day devoted to systems engineering to explain why a systems engineer was included and to get the whole team involved to define the needs, gather documents for requirements, agree upon the system boundaries, define the system architecture, and identify the interfaces between the subsystems. The day's agenda was led by the systems engineer as a demonstration of his potential contributions to the SEM2011 team. The day went smoothly, and all primary objectives were met.

Architecture. To create an initial system baseline, the systems engineer created an Architecture Design diagram, which was continuously updated. The Architecture Design itemized the 10 subsystems with the different components making up the complete system. Simplicity was essential during this process, and defining the system in a more detailed manner would have resulted in making the process too complex. Next, the responsible owners of each subsystem established a baseline configuration. Each team member owned at least one subsystem based on their educational background and expertise.

Interfaces. After defining the architecture design, the process of analyzing how the different subsystems interacted with each other could begin. The whole team gathered to analyze and define the subsystem dependencies and interfaces. Basic tools such as whiteboard and markers were used. The whole team contributed and there was a good discussion about where and how the interfaces between different subsystems should be set. There was also a discussion between the team members about details of the subsystems. The decision was made during the analysis that all the subsystems were made up of the different subcomponents. The systems engineer also identified the engineers responsible for the interfaces, which eventually minimized the risk of confusion later in the development of the system. The result of the interface documents led to changes in the placement of the engineers in the office, where people with a lot of interfaces sat together so the communication was easier. A further development of the interface document, to relate to the car design was made by the systems engineer to get a better illustration of the system dynamics. The system was divided into two documents for electronic and mechanical interfaces respectively.

Requirements validation. The system needs and requirements for the SEM car used the official rules from Shell as source documents. All data from Shell was analyzed to define the NTNU project requirements, since only by fulfilling the requirements from Shell would the car qualify for the competition by passing the technical inspection. If the requirements could not be validated onsite, the risk of losing time by doing modifications to the car before the race could jeopardize the outcome. The systems engineer made a Total System Requirements document connecting all the requirements from Shell mapped to the different subsystems using the specified subsystem id's to improve traceability.

Construction. Before the different subsystem designs were sent out for production, an extensive testing and verification phase was done on each mechanical subsystem using the respective subsystem document, and CAD (Computer Aided-Design) software. The reason for having these tests was to lower the risk of making the wrong subsystems and to eliminate flaws during the final design phase, rather than in rework, since the manufacturing involved long lead-times.

Visualization. A problem was discovered after all the Subsystem Documents were finished and published for the engineers. Even though all the files and information were accessible on NTNU's server for the engineers, they were not referenced consistently by the team members. As well it was not easy for the project managers and teaching supervisors to have a clear overview of the status of each subsystem. The systems engineer came up with the idea of having a Systems Engineering Wall, as shown in Figure 1, which illustrated the subsystems and components and used colors to illustrate the status of each component. In addition, the wall helped track configuration management.

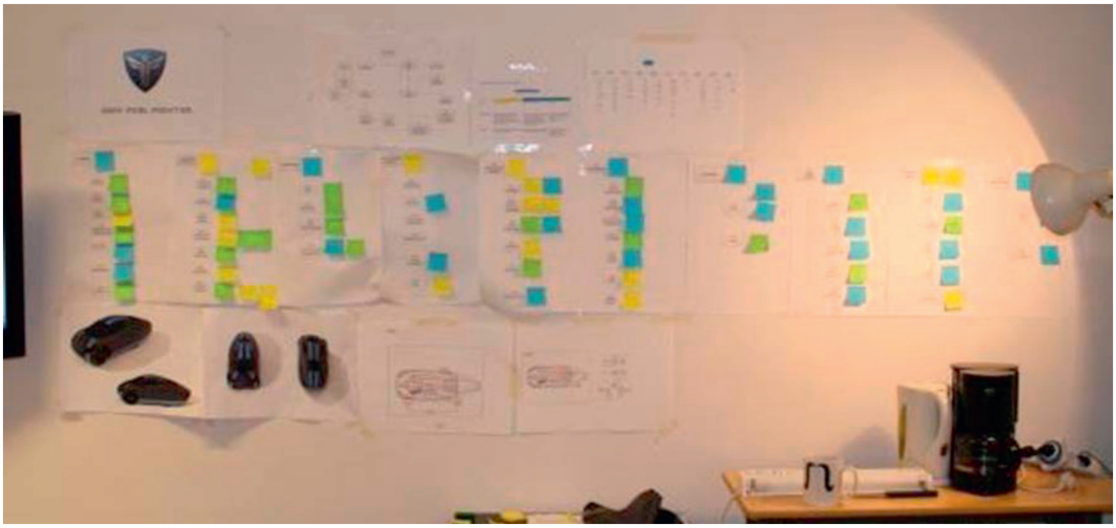

Figure 1. The Systems Engineering Wall (Welland 2011)

The Race – the ultimate Validation. If the system passes the technical inspection and finishes the race with a result, the system is considered validated by the customer/sponsor. The technical inspection is the first validation of the requirements to fulfill the rules of the Shell organizers. The inspection was passed without any annotations by Shell. Passing this first hurdle proved that the all the verification testing and the careful analysis of the stakeholder requirements had been worth the effort.

Did SE matter? Before the rest of the team could be influenced by the final result, the systems engineer interviewed some of the engineers on the way to the race and asked if systems engineering had any impact on the project.

One team member said that discovering issues related to configuration management and CAD testing before the production of the components had been beneficial. This also included the discovery of the issues during testing before the race. Last year's team (*i.e. SEM2010)* did not do any testing and had there been any tests conducted before the race, the system would have failed.

Another engineer said that systems engineering worked well, especially by helping to discover issues early. A third engineer said that the systems engineering approach was good and made the engineers think over different things that weren't thought about before. Having the systems engineer around to ask questions and search for the reasons was helpful.

The Wall. Team members were fascinated by the "Systems Engineering Wall" illustrating the documents produced and the real time status update using the different colors. The team members regularly looked at the wall and the system structure. The impression was that there was always a lot remaining to be done, but the wall helped the team members to structure the work they knew had to be done to finish their subsystems.

Conclusion. Simplicity was essential during the project and helped coordinate the activity of team members who each took ownership of a subsystem. Documentation uncovered from the prior year's work did not have any traceability to the subsystems, nor were there assignments to a responsible engineer for the different requirements. Ownership was critical during the process, saving time and helping the team to reach decisions faster. Interface specification and traceability from Shell requirements made it easy to understand the complete system, the subsystems and their components and easier to trace configuration through the system. Systems engineering really proved its value in the verification phases of the project because this is where a lot of issues were uncovered. Discovering issues during the verification phase was possible because of the clear requirements and permitted the project to maintain schedule and budget, notwithstanding supplier delays and other obstacles.

The systems engineering approach was immediately adopted by the following year's team. Early reports indicated that the SEM2012 team was able to benefit from the legacy of artifacts and practices created by the SEM2011 project team.

4.2. The SEM race 2012

The project team formed early and had very little trouble recruiting team members, including two systems engineers. Keeping with the tradition of the prior year, the author conducted her crash course in systems engineering, which established a team vocabulary and shared vision. Over the next three months the team made significant decisions to change the power system, and Shell made significant changes to the requirements, moving the race from a track to road, which mandated many changes to the suspension and other subsystems of the car. Despite these changes, the team stayed disciplined and followed a process similar to that described for SEM2011. One of the additional aspects of SEM2012's artifacts is that formal models were constructed using CORE® from Vitech.

The increased sophistication of the models, and the fact that the students not only applied the SE methods, but also were committed to leaving a good legacy for following teams are both characteristic of the success of this activity. As an added bonus these were the first students recruited by Norwegian industry, and all of them had jobs before graduation.

4.3. The SEM race 2013

The SEM2013 project team formed in September, the SE tutorial has been conducted and project has received requirements from Shell. The story continues.

5. Discussion and future work

The personal observations of the author are that the students enjoy practical activities. They become deeply involved in the work they are doing in the workshop and the laboratory. The best students are quickly selected for early placement usually in the firms of their choice. Follow-up contact with the students suggests that the one educational experience they draw upon the most is their participation in the SEM project.

Industry partners are happy for the opportunity to evaluate prospective employees by supporting projects and research on campus. The plan is to continue with activities already in place, and look for opportunities to introduce systems engineering methods to more students. There are also plans to expand the educational offerings into the workplace of industry partners interested in learning more about systems engineering.

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